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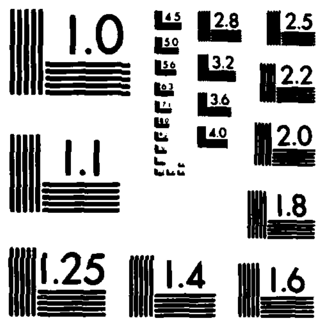


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ANNUAL REPORT
Joint Services Electronics Program
DAAG29–84–K–0024
April 1, 1984 – December 31, 1984

# TWO-DIMENSIONAL SIGNAL PROCESSING AND STORAGE AND THEORY AND APPLICATIONS OF ELECTROMAGNETIC MEASUREMENTS



JANUARY 1985



GEORGIA INSTITUTE OF TECHNOLOGY
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
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This is an annual report on research conducted under the auspices of the Joint Services Electronics Program. Specific topics covered are: digital signal processing, parallel processing architectures, two-dimensional optical storage and processing, hybrid optical/digital signal processing, electromagnetic measurements in the time domain, and automatic radiation measurements for near-field and far-field transformations.

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Joint Services Electronics Program

Contract DAAG29-84-K-0024

April 1, 1984 - December 31, 1984

# TWO-DIMENSIONAL SIGNAL PROCESSING AND STORAGE AND THEORY AND APPLICATIONS OF ELECTROMAGNETIC MEASUREMENTS

January 1, 1985

Georgia Institute of Technology
School of Electrical Engineering
Atlanta, Georgia 30332

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## TABLE OF CONTENTS

## I. OVERVIEW

This annual report covers the first nine months of research carried out under Contract DAAG29-84-K-0024. The research is part of the Joint Services Electronics Program and is administered by the U. S. Army Research Office. Research activities are concentrated in two areas: (1) Two-Dimensional Signal Processing and Storage, and (2) Theory and Application of Electromagnetic Measurements.

The research in two-dimensional signal processing and storage is concentrated in four major areas. These areas overlap and the research activities interact and reinforce one another. Research in Work Unit Number 1, *Multidimensional Digital Signal Processing*, is concerned with the theory, design, and implementation of digital signal representations and digital signal processing algorithms and systems. Work Unit Number 2, *Multiprocessor Architectures for Digital Signal Processing*, focusses upon hardware and software problems in the use of multiport memories and multiple processors for high-speed implementations of digital signal processing algorithms. The research in Work Unit Number 3, *Two-Dimensional Optical Storage and Processing*, is concerned with problems of using holographic information storage as the basis for multiport memories and for optical computation. Work Unit Number 4, *Two-Dimensional Optical/Electronic Signal Processing*, is concerned with the theory, implementation, and application of combined optical and electronic digital signal processing techniques.

The other two work units in the JSEP program are concerned with electromagnetic measurements. In Work Unit Number 5, *Electromagnetic Measurements in the Time- and Frequency-Domains*, research is concerned with both theoretical and experimental investigations of the use of time-domain and frequency-domain methods for measuring the characteristics of materials and electromagnetic systems. Work Unit Number 6, *Automated Measurements for Near- and Far-Field Transformations*, is concerned with assessing the accuracy of computed fields on the surface of lossy radomes and with compensating for probe effects when near-field measurements are made on spherical and arbitrary surfaces.

The report begins with a summary of the most significant accomplishments (in the judgement of the lab directors) during the period April 1, 1984 to December 31, 1984. Following this are brief reports on the individual work units. These reports list personnel supported and discuss in general terms the research that was carried out during the reporting period. Also included in each work unit report is a complete list of publications on the research during this period. Complete copies of these publications are available in the Annual Report Appendix.

## III. SIGNIFICANT RESEARCH ACCOMPLISHMENTS

The following accomplishments are, in the judgement of the laboratory directors, of particular significance and potential and are therefore worthy of special mention.

### 3.1 Optimal Multiprocessor Implementations of DSP Algorithms

The research in Work Unit Number 2 has lead to a new conceptual framework and a new formalism for the description and manipulation of synchronous multiprocessor implementations of highly structured algorithms such as those found in digital signal processing. Earlier work has focussed on a particular architecture termed skewed single instruction multiple data (SSIMD). This earlier research has lead to the discovery of a more general class of multiprocessor implementations that has been called *cyclo-static*. Recent research has shown how to automatically generate rate-optimal, delay-optimal, and processor-optimal cyclo-static realizations for fully specified recursive shift-invariant flow graphs. Cyclo-static implementations have all the advantages of SSIMD implementations with few of the disadvantages. In particular, at least one and often many rate-optimal implementation is always attainable, whereas for SSIMD, a rate-optimal implementation is not always possible. Likewise, at least one rate-optimal, delay-optimal implementation is always attainable. Delay-optimal implementations are seldom attainable for SSIMD. Like SSIMD, cyclo-static implementations are always processor-optimal, and so long as only optimal implementaions are sought, cyclo-static solutions can be found using efficient tree-searching procedures. However, optimal solutions for cyclo-static implementations always exist. Therefore it has been possible to write a program for the automatic generation of cyclo-static solutions from shift-invariant flow graphs. This program is the heart of a "cyclo-static compiler" which can generate control code for a broad class of synchronous MIMD machines.

### 3.2 New Results in Grating Diffraction Theory

A major achievement of the continuing research of Work Unit Number 3 has been the development of a rigorous coupled-wave theory of grating diffraction. Formerly, this theory was restricted to dielectric materials. Recently, it has been possible to extend the theory to obtain the first unified rigorous (with no approximations) theory of grating diffraction that applies to both dielectric and metallic materials and to planar (slab) and surface-relief structures. As a result of this new theory, it has been shown that a periodic surface on a dielectric can produce zero reflectivity for a given polarization and wavelength. Furthermore, the necessary surface requires only shallow grooves and is insensitive to changes in angle and grating parameters.

### 3.3 A New Algorithm for Pisarenko Decomposition

A new iterative algorithm has been developed for implementing the Pisarenko decomposition of a signal into a sum of nonharmonically related sinusoids in white noise. The method avoids a difficult eigenvalue computation and contains a built-in criterion for determining the required model order. It is currently being applied to two-dimensional spectrum estimation, spectral line tracking and harmonic decomposition of random processes in non-white noise.

WORK UNIT NUMBER 1

TITLE: Multidimensional Digital Signal Processing

SENIOR PRINCIPAL INVESTIGATOR: R. W. Schafer, Regents' Professor

SCIENTIFIC PERSONNEL:

M. H. Hayes, Assistant Professor
H. Kobatake, (Visiting Associate Professor)
R. M. Mersereau, Professor
C. Au Yeung, Graduate Research Assistant (Ph.D candidate)
J. E. Bevington, Graduate Research Assistant (Ph.D candidate)
C. C. Davis, Jr., Graduate Research Assistant (Ph.D. candidate)
A. Guessoum, Ph.D. recipient (June 1984)
A. Katsaggelos, Graduate Research Assistant (Ph.D. candidate)
P. Maragos, Graduate Research Assistant (Ph.D. candidate)

SCIENTIFIC OBJECTIVE:

The long term scientific objective of this research is to understand the means by which multidimensional signals such as images should be modelled and represented to facilitate the encoding, enhancement, and automatic extraction of information from such signals, and to develop, analyze and extend computer algorithms for these purposes.

RESEARCH ACCOMPLISHMENTS:

A. Fast Algorithms for the Multidimensional Discrete Fourier Transform

This work addressed the problem of designing efficient algorithms for the evaluation of very general multidimensional discrete Fourier transforms defined on arbitrary periodic multidimensional sampling lattices. A new mathematical formulation for the multidimensional DFT was introduced in which the DFT indices were viewed as elements in a lattice which could be manipulated geometrically. A Chinese remainder theorem for integer vectors was then derived which permitted a lattice generalization of the efficient one-dimensional prime factor and Winograd discrete Fourier transform algorithms. A variety of efficient algorithms was developed with careful attention paid to their computational efficiency. Software was developed which has been shared with research groups at Stanford University, North Carolina State University, and the Electromagnetics Group at Georgia Tech.

These results have appeared in the thesis by Guessoum and have been submitted for journal publication.

B. Image Segmentation by Texture

Work has continued on a project in image segmentation by texture. A maximum likelihood detector of the boundary between the two regions of different texture has been discovered and practical simplifications have been made which are partially successful. The resulting detector makes use of 2-D linear prediction residual signals in its classification. We have recognized, however, that this type of classification cannot be performed at the sample (pixel) level; context and global information is important. A framework for encapsulating "higher-level" information, which is updated with various pixel level measurements has been formulated and programmed, but has not yet been extensively tested.

The results on the maximum likelihood boundary detector has been presented at a conference. The other results are still too preliminary.

C. Reconstruction of Multidimensional Signals from Projections

We are looking at the use of iterative signal restoration algorithms applied to the reconstruction of multidimensional signals from projections. This problem has applications in synthetic aperture radar (spotlight mode), computerized tomography, and nondestructive testing. The use of iterative algorithms for this problem is not original although we have proposed some novel variations on these algorithms. The iterative formalism is a useful one since it allows constraints to be placed on the solution. Two new reconstruction algorithms are under study, one of which updates the estimate of the unknown by incorporating information from pairs of projections, and another which works with filtered projections to improve algorithm convergence. These results are not yet ready for publication.

D. Constrained Iterative Signal Restoration

New results in this area have resulted from the application of the regularization method of solving ill-posed problems. Considerable progress has been made toward controlling the effects of noise in image deblurring problems. Progress has also been made in nonstationary image restoration through the development of a technique for incorporating constraints based upon knowledge of human visual perception into the restoration procedure.

E. A Unified Theory of Translation-Invariant Image Processing Systems

The theory of mathematical morphology seeks to quantitatively represent geometrical structure in images. The principles of this theory have been applied to develop a general theory for translation invariant image processing transformations. This theory includes as special cases, median or order-statistics filters and an interesting class of linear systems. Also included is the skeleton transformation, which has been shown to have attractive properties for image coding and the detection of geometric shapes in images.

F. A New Algorithm for Pisarenko Decomposition

A new iterative algorithm has been developed for implementing the Pisarenko decomposition of a signal into a sum of nonharmonically related sinusoids in white noise. The method avoids a difficult eigenvalue computation and contains a built-in criterion for determining the required model order. It is currently being applied to two-dimensional spectrum estimation, spectral line tracking and harmonic decomposition of random processes in non-white noise.

PUBLICATIONS

Theses:

1. A. Guessoum, "Fast Algorithms for the Multidimensional Discrete Fourier Transform," Ph.D. Thesis, Georgia Institute of Technology, June 1984.

Books or Chapters in Books:

1. D. E. Dudgeon and R. M. Mersereau, Multidimensional Digital Signal Processing, Prentice-Hall, Englewood Cliffs, NJ, 1984.

2. M. H. Hayes, "Signal Reconstruction from Spectral Phase or Spectral Magnitude," in Advances in Computer Vision and Image Processing, vol. 1, (T. S. Huang, Ed.) JAI Press, 1984.

Journal Articles (Published or Accepted):

1. A. K. Katsaggelos, J. Biemond, R. M. Mersereau, and R. W. Schafer, "An Iterative Method for Restoring Noisy Blurred Images," Circuits, Systems, and Signal Processing, vol. 3, no. 2, June 1984.

2. P. A. Maragos, R. W. Schafer, and R. M. Mersereau, "Two-Dimensional Linear Prediction and Its Application to Adaptive Predictive Coding of Images," IEEE Transactions on Acoustics, Speech and Signal Processing, accepted for publication in December 1984.

Papers in Conference Proceedings:

1. D. M. Thomas and M. H. Hayes, "Procedures for Signal Reconstruction from Noisy Phase," Proc. 1984 Int. Conf. on Acoust., Speech and Signal Processing, pp. 31.1.1-31.1.4, March 1984.

2. J. E. Gaby and M. H. Hayes, "Artificial Intelligence Applied to Spectrum Estimation," Proc. 1984 Int. Conf. on Acoust., Speech and Signal Processing, pp. 13.5.1-13.5.4, March 1984.

3. P. A. Maragos, R. M. Mersereau, and R. W. Schafer, "Multichannel Linear Predictive Coding of Color Imaging," Proc. 1984 Int. Conf. on Acoustics, Speech and Signal Processing, pp. 29.5.1-29.5.4, March 1984.

4. J. E. Bevington and R. M. Mersereau, "A Maximum Likelihood Approach to Image Segmentation by Texture,' Proc. 1984 Int. Conf. on Acoustics, Speech and Signal Processing, pp. 32.7.1-32.7.4, March 1984.

5. P. A. Maragos and R. W. Schafer, "Morphological Skeleton Representation and Coding of Binary Images," Proc. 1984 Int. Conf. on Acoustics, Speech and Signal Processing, pp. 29.2.1-29.2.4, March 1984.

6. A. K. Katsaggelos, J. Biemond, R. M. Mersereau, and R. W. Schafer, "An Iterative Method for Restoring Noisy Blurred Images," Proc. 1984 Int. Conf. on Acoustics, Speech and Signal Processing, pp. 37.2.1-37.2.4, March 1984.

7. R. M. Mersereau, "Iterative Algorithms for Deconvolution and Reconstruction of Multidimensional Signals From Their Projections," Nato Advanced Study Institute on Adaptive Methods in Underwater Acoustics.

Papers Submitted:

1. A. Guessoum and R.M. Mersereau, "Fast Algorithms for the Multidimensional Discrete Fourier Transform," submitted to IEEE Trans. Acoustics, Speech and Signal Processing.

2. M. H. Hayes and M. C. Clements, "An Iterative Approach to Pisarenko's Harmonic Decomposition," submitted to IEEE Trans. Acoustics, Speech and Signal Processing.

3. A. Guessoum and R. M. Mersereau, "Fast Algorithms for the Multidimensional Discrete Fourier Transform," submitted to IEEE Trans. Acoustics, Speech and Signal Processing.

4. A. K. Katsaggelos, J. Biemond, R. M. Mersereau, R. W. Schafer, "Nonstationary Iterative Image Restoration," accepted, 1985 IEEE Int. Conf. on Acoustics, Speech and Signal Processing.

5. A. K. Katsaggelos, J. Biemond, R. M. Mersereau, and R. W. Schafer, "A General Formulation of Constrained Iterative Restoration Algorithms," accepted, 1985 IEEE Int. Conf. on Acoustics, Speech and Signal Processing.

6. P. A. Maragos and R. W. Schafer, "A Unification of Linear, Median, Order-Statistics and Morphological Fitlers Under Mathematical Morphology,' accepted, 1985 IEEE Int. Conf. on Acoustics, Speech and Signal Processing.

7. M. H. Hayes and M. C. Clements, "An Iterative Approach to Pisarenko's Harmonic Decomposition," accepted, 1985 Int. IEEE Conf. on Acoustic, Speech and Signal Processing.

8. A. Guessoum and R.M. Mersereau, "Solution to the Indexing Problem of Multidimensional DFTs on Arbitrary Sampling Lattices," accepted, 1985 IEEE Int. Conf. on Acoustics, Speech and Signal Processing.

9. M. H. Hayes, M. A. Clements, and D. Mitchell Wilkes, "Iterative Harmonic Decomposition of Nonstationary Random Processes: Theory and Application to Spectral Line Tracking," submitted for publication in Proc. Int. Conf. on Math. in Signal Processing.

## WORK UNIT NUMBER 2

TITLE: Multiprocessor Architectures for Digital Signal Processing

SENIOR PRINCIPAL INVESTIGATOR: T. P. Barnwell, III, Professor

SCIENTIFIC PERSONNEL:

C. J. M. Hodges, Research Engineer
D. A. Schwartz, (Ph.D. candidate)
S. H. Lee, (Ph.D. candidate)
M. J. T. Smith, (Ph.D. candidate)

SCIENTIFIC OBJECTIVE:

The objective of this research is to develop techniques for the automatic generation of optimal and near-optimal implementations for a large class of Digital Signal Processing (DSP) algorithms on digital machines composed of multiple processors.

RESEARCH ACCOMPLISHMENTS:

This research is centered on the problem of generating highly efficient implementations for a large class of DSP algorithms using multiple programmable processors. This problem is fundamental to many areas of activity, including VLSI design, implementations using arrays of state machines, signal processing chips, or microprocessors, and implementations using networks of general purpose computers.

DSP algorithms are unique in the sense that they usually are both highly structured and highly computationally intense. For this reason, it is often possible to achieve extremely efficient multiprocessor implementations in which the data precedence relations (that is to say the control functions) are maintained through the system synchrony and the system architecture, and every cycle of every arithmetic processor is applied directly to the fundamental operations of the algorithm. The basic goal of this research is to develop automatable techniques for the generation of such synchronous multiprocessor implementations from intrinsically non-parallel algorithm descriptions in such a way that the resulting implementations are both definably and meaningfully optimal. In short, we are developing multiprocessor compilers for DSP algorithms which can be used to generate optimal multiprocessor implementations for both discrete component and VLSI implementations.

Historically, this research has emphasized a set of techniques which we have named Skewed Single Instruction Multiple Data, or SSIMD, realizations. SSIMD implementations are generally realized on synchronous multiprocessors systems composed of many identical programmable processors. In SSIMD implementations, all of the processors execute exactly the same program using a computational mode in which the instruction execution times on the individual processors are skewed. SSIMD implementations have proven to have many desirable properties for DSP implementations. First, since all SSIMD implementations involve only one program, the problem of finding the best multiprocessor implementation reduces to the task of finding the best single processor implementation. Second, given any single processor program suitable for SSIMD implementations, it is possible to compute bounds for the full multiprocessor realization, thereby measuring in very fine grain the quality of the realization. These bounds include the SSIMD sample period bound, which is the minimum achievable time between the processing of input points; the SSIMD delay bound, which is the minimum achievable latency between the arrival on an input and the generation of the corresponding output; and the SSIMD processor bound, which is the minimum number of processors required to achieve the SSIMD sample period bound. Third, and more important, these bounds are not only easily computable, but also easily achievable. In particular, all SSIMD realizations which utilize fewer processors than the processor bound are perfectly efficient (processor optimal) in the sense that an N processor implementation is exactly N time faster than a one processor realization. Finally, the communications architecture required by SSIMD implementations is completely controllable through the specification of the delay (pipeline register) structure within the algorithm itself. For SSIMD realizations, it is always possible to realize the algorithm using a unidirectional nearest neighbor communications structure, but more complex communications architectures can be easily used to advantage if they are available. SSIMD realizations have many advantages for DSP realizations, particularly when compared to such approaches as systolic arrays, wavefront processors, SIMD and general MIMD solutions. In particular, SSIMD solutions tended to be faster, more efficient, and easier to find than the competing techniques. Most of the important results obtained over the past three years have resulted from a systematic attempt to understand the nature of the advantages which seemed to be inherent in the SSIMD approach.

We now know that SSIMD realizations are a special case of a more general class of synchronous multiprocessor implementations which we have named Cyclo-static realizations. The SSIMD results were all derived using a formalism which dealt with programs, that is to say sets of instructions for the control of arithmetic processors. We have now developed a similar formalism which deals not with programs, but with algorithms. In particular, we have introduced a three level formalism which allows for the simultaneous description and manipulation of a very large class of DSP algorithms. The three levels of the formalism -- called the graph theoretic level, the matrix level, and the link-list level -- are all mathematically equivalent formalisms each of which is particularly appropriate to understanding or implementing different parts of the theory. The graph theoretic level is most appropriate for conceptualizing the basic techniques. The matrix level is most appropriate to conceptualizing the associated automation techniques. And the link-list level is most appropriate to the actual computer realizations of the optimization techniques.

The algorithms addressed by this theory are those which can be described using fully-specified shift-invariant flow graphs. These graphs are similar to the more familiar shift-invariant signal flow graphs except that the nodes can contain any operators which can be realized by the processors to be used in the final realization. Given such a flow graph, and given the operation timings for the constituent processor which is to be used in the multiprocessor implementation of the flow graph, it is possible to compute absolute bounds on the multiprocessor realization. In particular, three bounds can be computed. The sample period bound is the smallest sample period at which the algorithm may be implemented. The delay bound is the shortest achievable period between an input and a corresponding output. And the processor bound is the fewest processor which can be used to achieve the sample period bound. These bounds give rise to a very fine-grained definition of optimality. An implementation is rate-optimal if it achieves the sample period bound. An implementation is delay-optimal if it achieves the delay bound. An implementation is processor-optimal if it is either perfectly efficient (factor N speedup) or if it achieves the sample period bound using the number of processors specified by the processor bound.

Last year, the application of our new formalism to the SSIMD approach resulted in the development of an SSIMD compiler for signal flow graphs. This compiler, which can be configured to generate code for a large class of discrete and VLSI multiprocessor machines, is currently configured to generate code for the eight-processor, LSI-11 based multiprocessor which has been designed and implemented as part of this research. This compiler always finds a rate-optimal SSIMD implementation if it exists, and finds the best SSIMD implementation if it does not. Because of the great insight attained in the computation of the bounds, it is fairly simple to find a rate-optimal solution if it exists. It is less efficient to find the best sub-optimal solution if that is what is required. SSIMD realizations are always processor-optimal, often rate-optimal, and seldom delay-optimal.

The application of our new formalism to the systolic approach resulted in a rigorous procedure for transforming shift-invariant flow graphs into systolic realizations. This procedure, which can be fully automated, constitutes a formal procedure for both the generation and the verification of systolic implementations. But more important, this procedure showed very clearly the relationship between SSIMD and systolic implementations. Whereas systolic implementations constituted a full parsing of the algorithm in space, the SSIMD approach constituted a full parsing of the algorithm in time, followed by a mapping of time into space. Both the SSIMD and the systolic approach are limited special cases of synchronous multiprocessor implementations, and both have the virtue that they simplify the problem to the point at which it may be solved. Both have the disadvantage that, in simplifying the problem, they have over-constrained the resulting implementations.

This year, major advances have been made in three areas. The first, and most important, is the area of the automatic generation of rate-optimal, delay-optimal, and processor-optimal cyclo-static realizations for fully specified recursive shift-invariant flow graphs. Cyclo-static implementations have all of the advantages of SSIMD implementations without most of the disadvantages. In particular, at least one (often many) rate optimal implementation is always attainable, whereas for SSIMD a rate-optimal implementation was not always achievable. Likewise, at least one rate-optimal, delay-optimal implementation is always attainable. Delay-optimal implementations are seldom attainable for SSIMD. Like SSIMD, cyclo-static implementations are always processor-optimal. Also like SSIMD, so long as only optimal implementations are sought, cyclo-static solutions can be found using efficient tree-searching procedures. Unlike SSIMD, however, optimal solutions for cyclo-static schedules always exist.

Based on the above results (this is mostly the Ph.D. research of David A. Schwartz), a program for the automatic generation of cyclo-static solutions from shift-invariant flow graphs has been demonstrated. This program is the essential part of a 'cyclo-static compiler' which can generate control code for a broad class of synchronous MIMD machines.

The second area in which results have been attained is the area of more *efficient* techniques for find sub-optimal SSIMD realizations. One of the outstanding problems with the existing SSIMD compiler is that when no optimal implementation exists, finding the best sub-optimal implementation is a computationally intensive process. The new techniques systematically apply constraints to the search for non-optimal SSIMD solutions so as to dramatically reduce the computational cost. A program to realize the techniques developed has been written. This is largely the Ph.D. research of S. H. Lee.

The final area in which progress has been made is in a new formalism for describing maximally decimated analysis/reconstruction systems based on filter banks. Such systems constitute a class of short-time-frequency representations for signals, and are useful for one and two dimensional frequency domain coding and processing. A major earlier result in this area (1983) was the development of techniques for generation of high-quality filter banks which achieved exact reconstruction in the absence of noise. The new formalism extends these results to a much broader class of systems, as well as pulling together many other published solutions under a single umbrella. This is largely the Ph.D. thesis work of M. J. T. Smith.

PUBLICATIONS:

Theses:

1. M.J.T. Smith, "Exact Reconstruction Analysis/Synthesis Systems and Their Application to Frequency Domain Coding," Ph.D. Thesis, Georgia Institute of Technology, December 1984.

Papers in Conference Proceedings:

1. D. A. Schwartz and T. P. Barnwell III, "A Graph Theoretic Technique for the Generation of Systolic Implementations for Shift-Invariant Flow Graphs," Proc. of the International Conference on Acoustics, Speech and Signal Processing, March 1984.

2. D. A. Schwartz and T. P. Barnwell III, "Increasing the Parallelism of Filters Through Transformation to Block State Variable Form," Proc. of the International Conference on Acoustics, Speech and Signal Processing, March 1984.

3. M.J.T. Smith and T.P. Barnwell, III, "A Procedure for Designing Exact Reconstruction Filter Banks for Tree-Structured Subband Coders," Proc. ICASSP'84, March 1984.

Papers Submitted or Accepted:

1. S. H. Lee, C. J. M. Hodges, and T. P. Barnwell III, "An SSIMD Compiler for the Implementation of Linear Shift-Invariant Flow Graphs," accepted, to appear at Int. Conf. on Acoustics, Speech and Signal Processing.

2. D. A. Schwartz and T. P. Barnwell III, "Cyclo-static Multiprocessor Scheduling for the Optimal Realization of Shift-Invariant Flow Graphs," accepted, 1985 IEEE Int. Conf. on Acoustics, Speech and Signal Processing.

3. S. H. Lee, C. J. M. Hodges, and T. P. Barnwell III, "An SSIMD Compiler for the Implementation of Linear Shift-Invariant Flow Graphs," accepted, 1985 IEEE Int. Conf. on Acoustics, Speech and Signal Processing.

4. M.J.T. Smith and T.P. Barnwell, III, "A New Formalism for Describing Analysis/Reconstruction Systems Based on Maximally Decimated Filter Banks," accepted, 1985 IEEE Int. Conf. on Acoustics, Speech and Signal Processing.

WORK UNIT NUMBER 3

TITLE: Two-Dimensional Optical Storage and Processing

SENIOR PRINCIPAL INVESTIGATOR: T. K. Gaylord, Professor

SCIENTIFIC PERSONNEL:

M. G. Moharam, Assistant Professor
C. C. Guest, Post Doctoral Fellow
M. M. Mirsalehi, Graduate Research Assistant (Ph.D. candidate)
A. Knoesen, Graduate Research Assistant (Ph.D. candidate)

SCIENTIFIC OBJECTIVE:

The long-term scientific objective of this research is to develop broadly based, theoretical and experimental knowledge of high-capacity, high-throughput, two-dimensional optical information storage and two-dimensional optical signal processing. This would bring together a range fo concepts from basic physics to signal processing in its most generalized form. An optical digital parallel processor based on truth-table look-up processing implemented in the form of a content-addressable memory would be developed and tested.

RESEARCH ACCOMPLISHMENTS:

A. Residue Number System Truth-Table Look-Up Processing

Truth-table look-up processing using binary coded residue numbers was investigated for full-precision addition and multiplication for implementations using either electronics or optical technologies. The logically minimized numbers of input combinations needed for each operation are presented for moduli 2-23. The moduli sets that require the minimum number of reference patterns are determined for addition and multiplication of 4,8,12, and 16 bit words.

This work showed that the sizes of the truth tables are manageable. A specific procedure for selecting the modulin and minimizing the truth tables was presented. This work was published in the IEEE Transactions on Computers.

B. EXCLUSIVE OR Optical Logic

Theoretical and experimental results were presented for parallel EXCLUSIVE OR processing using thick Fourier holograms. The data pages used contained 1024 bits in a 32 x 32 format. A holographically stored data page is reconstructed together with an input data page that is imaged through the system. The amplitudes of the two wave fronts are adjusted to be equal, and their relative phase is adjusted to be $180^\circ$, thus producing the bit-by-bit EXCLUSIVE OR operation between the pages. Using an expanded reference beam for the geometrical configuration treated, it is calculated that the average dynamic range between a 0 and a 1 in the output power would be 17.4 dB. Experimentally, it is shown that excellent EXCLUSIVE OR results are obtainable. An average dynamic range of 7.7 dB was measured, the decrease from the calculated value being primarily due to noise in the video method of detection used in the measurements. The probabilities of miss and false alarm and the total probability of error were also measured. The use of a small diameter reference beam, necessary in some applications, causes a large mismatch in the shapes of the two wave fronts, thus degrading the EXCLUSIVE OR results. It is shown theoretically and experimentally that using an aperture at the recording material produces partial compensation of the wave fronts, thus improving the EXCLUSIVE OR results.

This work was published in Applied Optics.

C. Multi-Level Coding for Residue Number System Truth-Table Look-Up Processing.

The effect of coding level on the number of required reference patterns in a residue-based content-addressable-memory (CAM) has been examined. For moduli expressable as $M=p^n$, where p is a prime number and n is a positive integer greater than one, use of p-level coding reduces the number of reference patterns to be stored relative to other coding levels. In general, the prime factors that divide a modulus can be used to find the coding level that corresponds to the minimum number of reference patterns. An optical implementation of multi-level coded CAM has been introduced. The minimization of minterms in multiple-valued logic has been briefly discussed and the optical methods of achieving different types of reduced terms have been presented.

This work will be presented at the Optical Computing Conference in March 1985.

D. Unified Theory of Grating Diffraction

The first unified rigorous (without approximations) theory of grating diffraction that applied to 1) dielectric and metallic materials, and to 2) planar (slab) and surface-relief structures has been developed by us. Parts of this work have been published previously. This new unified rigorous coupled-wave analysis will be recognized quickly since our past work restricted to dielectric materials is widely known and accepted.

This work has not yet been published.

E. Antireflection Properties of Dielectric Gratings

It has been shown that a periodic surface on dielectric can produce zero reflectivity for a given polarization and wavelength. Further, the necessary surface requires only shallow grooves and is insensitive to changes in angle and grating parameters.

This is being investigated at the present time.

## PUBLICATIONS:

### Journal Articles:

1. T.K. Gaylord, and C. C. Guest, "Optical Interferometric Liquid Gate Plate Positioner," Review of Scientific Instruments, vol. 55, pp. 866-868, June 1984.

2. C. C. Guest, M. M. Mirsalehi, and T. K. Gaylord, "Residue Number System Truth-Table Look-Up Processing: Moduli Selection and Logical Minimization," IEEE Transactions on Computers, vol. C-33, pp. 927-931, October 1984.

3. M. G. Moharam, T. K. Gaylord, G. T. Sincerbox, H. Werlich, and B. Yung, "Diffraction Characteristics of Photoresist Surface-Relief Gratings," Applied Optics, vol. 23, pp. 3214-3220, September 15, 1984.

4. C. C. Guest, M. M. Mirsalehi, and T. K. Gaylord, "EXCLUSIVE OR Processing (binary image subtraction) using Thick Fourier Holograms," Applied Optics, vol. 23, pp. 3444-3454, October 1, 1984.

### Journal Papers Submitted or Accepted:

1. T. K. Gaylord, and M. G. Moharam, "Analysis and Applications of Optical Diffraction by Gratings," Proceedings of the IEEE, vol. 73, pp. xxx-xxx, 1985. (invited)

2. T. K. Gaylord, M. M. Mirsalehi, and C. C. Guest, "Optical Digital Truth-Table Look-Up Processing," Optical Engineering, vol. 24, pp. xx-xx, January/February, 1985. (invited)

3. M. M. Mirsalehi, and T. K. Gaylord, "Comments on Direct Implementation of Discrete and Residue-Based Functions Via Optimal Encoding: A Programmable Array Logic Approach," IEEE Transactions on Computers, vol. C-33, pp. xxx-xxx, 1984. (submitted)

## INTERACTIONS AND TECHNOLOGY TRANSFER:

The rigorous coupled-wave analysis of grating diffraction as developed by us has been adopted by Kaiser Optical for the design of the holographic head-up display in the F-15 fighter aircraft.

WORK UNIT NUMBER 4

TITLE: Two-Dimensional Optical/Electronic Signal Processing

SENIOR PRINCIPAL INVESTIGATOR: W.T. Rhodes, Professor

SCIENTIFIC PERSONNEL:

J.N. Mait, Graduate Research Assistant (Ph.D. candidate)
R.W. Stroud, Graduate Research Assistant (Ph.D. candidate)

SCIENTIFIC OBJECTIVE:

The long term scientific objective of this research is to gain a good understanding of the capabilities and limitations of hybrid optical/electronic methods for high throughput processing of 2-D signal information and to develop new and widely applicable techniques based on such methods. Emphasis is placed on establishing the capabilities of systems that mate well with digital signal processing systems.

RESEARCH ACCOMPLISHMENTS:

A. Bipolar Incoherent Spatial Filtering

Our original objective in this area was to develop effective methods for bipolar spatial filtering using incoherent optical systems that are simple to implement and efficient with respect to light utilization. That objective was augmented with the additional goal of maximizing overall system dynamic range in the case where optical and digital subsystems are combined with a scanning operation in between.

Work the past year has seen completion of an elegant unifying theory of pupil function specification for the two kinds of two-pupil hybrid optical/electronic spatial filtering methods (one method involving interference of light from the two pupils, the other method not). Further, a two-step algorithm has been developed for designing pupil functions that are optimal in the sense of reducing noise and enhancing contrast. In this work suitable point and global performance measures for noise and contrast have been developed. The pupil function design algorithms, which are based on constrained iterative methods currently of considerable interest in the digital image restoration community, were tested to verify that the optimal pupil functions provide a measureable improvement over nonoptimal pupil functions. A doctoral dissertation on this work should be completed by January 1985. Manuscripts for publication will be submitted shortly thereafter.

B. Opto-Electronic Processor Architectures

Work during the past year has emphasized the development and comparison of different architectures, based on multi-transducer acoust-optic device technology, for highspeed matrix-vector and matrix-matrix processing. Two concerns have received particular attention: (1) fundamental limitations on processor capabilities and (2) increasing processor accuracy through quasi-digital methods. Developments in both areas are reported in a recent invited paper in the Proceedings of the IEEE.

Algebraic optical processing has received considerable attention at a number of research organizations during the past two to three years, and several resonably large contracts are currently being funded by DOD laboratories for the construction of opto-electronic matrix-vector processors. Unfortunately, our studies, as well as those of others, indicate that the digital accuracy opto-electronic processors that can be constructed on the basis of current ideas will have no significant speed advantage over all-electronic counterparts (weight and power consumption might be better). As a consequence, we plan a shift in emphasis under this sub-area away from acousto-optic device technology and the DMAC (digital multiplication by analog convolution) approach for achieving digital accuracy. We plan to place greater emphasis on investigating the potential of arrays of bistable opto-electronic devices for algebraic and two-dimensional signal processing.

PUBLICATIONS:

Journal Articles:

1. William T. Rhodes and Peter S. Guilfoyle, "Acousto-Optic Algebraic Processing Architectures," Proceedings of the IEEE, Vol. 72, No. 7, July 1984 (special issue on Optical Computing), pp. 820-830 (invited).

Papers in Conference Proceedings:

1. H. John Caulfield and William T. Rhodes, "Optical Algebraic Processing Architectures and Algorithms," in Optical Computing, John A. Neff, ed. (SPIE, Vol. 456, Jan. 1984) (invited).

Papers at Conferences without Proceedings:

1. Joseph N. Mait, "Optimal Design of Pupil Functions for Bipolar Incoherent Spatial Filtering," presented at the 1984 Annual Meeting of the Optical Society of America, San Diego, October 1984.

Papers Submitted:

1. William T. Rhodes and M. Koizumi, "Complementary Source and Pupil Distributions for Image Enhancement," submitted for publication.

2. William T. Rhodes, Keith D. Ruehle, and Robert W. Stroud, "Two-Dimensional Optical Fourier Transform Holography by Time-Integration Method," submitted for publication.

INTERACTIONS WITH DOD LABS:

Visited U.S. Army Engineer Topographic Laboratory in April 1984 for discussions with Dr. M. McDonnel and Dr. R. Leighty.

Visited Naval Research Laboratory in April 1984 for discussions with Dr. R. Athale and Dr. H. Szu in the Optical Sciences Division.

A private company, Quantum Diagnostics, Inc., on Long Island, is currently constructing an ultra-high-quality optical/electronic system for bipolar incoherent spatial filtering that is based on concepts developed under this Work Unit. According to discussions with their research director the system is intended for commercial rather than military applications. However, their success with the system will have clear implications for military uses also.

## REFERENCES


1. W.T. Rhodes and P.S. Guilfoyle, "Acoustooptic algebraic processing architectures," Proceedings of the IEEE, vol. 72, pp. 820-830 (1984).

2. D.A.B. Miller et al., "Quantum well optical modulators and Self Electrooptic Effect Devices (SEED's)," paper to be presented at March 1985 Optical Society of America Topical Meeting on Optical Computing.

3. Robert Seymore, GTE Laboratories, private communication, 5 December 1984.

4. Alan Huang, "Parallel algorithms for optical digital computers," in Proceedings of the 10th International Optical Computing Conference, (IEEE Cat. No. 83CH1880-4, 1983), pp. 13-17.

5. K.H. Brenner and A. Huang, "An optical processor based on symbolic substitution," paper to be presented at March 1985 Optical Society of America Topical Meeting on Optical Computing.

6. See, e.g., D. Psaltis and N. Farhat, "A new approach to optical information processing based on the Hopfield model," to appear in Optics Letters.

## WORK UNIT NUMBER 5

TITLE: Electromagnetic Measurements in the Time and Frequency Domains

SENIOR PRINCIPAL INVESTIGATOR: G. S. Smith, Professor

SCIENTIFIC PERSONNEL:

J. D. Nordgard, Professor
W. R. Scott, Jr., Graduate Research Assistant (Ph.D. candidate)

SCIENTIFIC OBJECTIVE:

The broad objective of this research is to develop new methodology for making electromagnetic measurements directly in the time domain or over a wide bandwidth in the frequency domain. This research includes the development of the theoretical analyses necessary to support the measurement technqiues. One aspect of the research is the systematic study of radiating structures placed near or embedded in material bodies. In a practical situation the radiator might serve as a diagnostic tool for determining the geometry, composition or electrical constitutive parameters of the body.

RESEARCH ACCOMPLISHMENTS:

The research conducted during the last year was concentrated on the topic "Measurement of the Electrical Constitutive Parameters of Materials Using Antennas." This research involves the study of three separate configurations for measuring the constitutive parameters of a material:

A. the monopole antenna of moderate electrical size

B. the open-circuited coaxial line of general electrical length

C. the monopole antenna of general electrical length.

The research involving configurations A. and B. is complete, and journal articles describing the results are in preparation.

A brief description of the research accomplishments for these two topics follows.

A. Monopole Antenna

A general technique is developed for measuring the electrical constitutive parameters of a material using a monopole (dipole) antenna. A normalized impedance that is only a function of the dimensionless parameter kh (wave number length) is defined for the antenna. The normalized impedance is expressed as a rational function, and the coefficients in this function are determined from a measurement of the impedance in a standard medium.

The impedance measured in a material with unknown constitutive parameters is used with the rational function to form a polynomial in kh. The constitutive parameters of the medium are determined from a root of this polynomial.

The measurement technique was implemented for a rational function of order three. The constitutive parameters of the alcohol 1-butanol and saline solutions were measured over a range of frequencies using the technique with cylindrical and conical monopole antennas. The measured constitutive parameters are in good agreement with those determined by previous investigators.

B. Open-Circuited Coaxial Line

The open-circuited coaxial line of general length is studied in detail as a sample holder for broadband measurements of the dielectric permittivity. The multivalued nature of the inverse function is described in detail. The error that results from passing onto the wrong branch of the inverse function is analyzed; a procedure that can prevent passing onto the wrong branch is developed. Contour graphs are constructed that quantify the effects of these two errors on the measured permittivity.

A time-domain measurement system was constructed, calibrated, and used with an open-circuited sample cell to measure the permittivities of several primary alcohols over the frequency range 50MHz<f<2GHz. The measured relaxation spectra for these alcohols are in good agreement with those determined by previous investigators.

PUBLICATIONS:

Journal Articles:

1. G. S. Smith, "Limitations on the Size of Miniature Electric Field Probes," IEEE Trans. Microwave Theory and Tech., vol. MIT-32, pp. 594-600, June 1984.

Papers at Conferences with Proceedings:

1. G. S. Smith, "Limitations on the Size of Miniature Electric Field Probes-The Smallest Dipoles," 1984 IEEE Antenna and Propagation Society, International Symposium and National Radio Science Meeting (URSI), Boston, MA, June 1984.

2. G. S. Smith and L. C. Shen, "The Circular Loop Antennas in the Presence of a Material Body," (invited paper) XXIst General Assembly of the International Union of Radio Science (URSI), Florence, Italy, August-September 1984.

Papers Submitted:

1. G. S. Smith and J. D. Nordgard, "Measurement of the Electrical Constitutive Parameters of Materials Using Antennas," submitted for publication.

INTERACTION WITH DOD LABS:

During the year a study of an existing buried antenna was carried out for the Air Force (RADC, Griffiss, AFB). The experimental portion of this study made use of measurement techniques and facilities developed at Georgia Tech on the Joint Services Electronics Program.

## WORK UNIT NUMBER 6

TITLE: Automated Radiation Measurements for Near- and Far-Field Transformations

SENIOR PRINCIPAL INVESTIGATOR: E.B. Joy, Professor

SCIENTIFIC PERSONNEL:

W.M. Leach, Jr., Professor
G.K. Huddleston, Associate Professor (Resigned July 1984)
J.M. Rowland, Graduate Research Assistant (Ph.D. candidate)
R.E. Wilson, Graduate Research Assistant (Ph.D. candidate)
A.J. Julian, Jr., Graduate Research Assistant (Ph.D. candidate)
Y. Kanai, Graduate Research Assistant (M.S. candidate)

SCIENTIFIC OBJECTIVE:

The long term objective of this research is to understand the near field and far field coupling between antennas in the presence of scatters. Special emphasis is placed on determination of limits of accuracy in the measurement of the fields radiated or scattered by an antenna-under-test by a second antenna and to develop techniques and computer algorithms for compensation of such measurements due to known geometrical or electromagnetic anomalies.

RESEARCH ACCOMPLISHMENTS:

A. *Near-Field Cross-Section Measurement* Technique

Initial work has been completed on the plane wave scattering description of near-field coupling among three antennas. Antenna number one is viewed as the source of electromagnetic radiation, antenna number two is viewed as a scatterer of electromagnetic energy and the third is viewed as the receiver of electromagnetic radiation. This general formulation can model both bistatic and monostatic radar cross section measurement systems, both in the near-field and far-field. The model is capable of predicting both far-field bistatic and monostatic radar crossections from near-field measurements. The model has been verified for a single plane wave illumination, bistatic measurement. The model has not been verified for the monostatic case and such verification is important as a key assumption (the application of the "Bistatic Theorem" approximation) must be involked for far field prediction. Preliminary results of this effort were reported at the Antenna Measurement Technique Association Symposium in October, 1984.

B. Plane Wave Spectrum Radome Analysis Including Reflections

An existing plane wave spectrum radome analysis computer algorithm was extended to include inner radome reflections. A transmitting formulation was applied to model the antenna within the radome. The antenna is described by its plane wave spectrum and each plane wave is propagated through the radome multilayer wall. This algorithm was extended by the determination of the plane wave reflection coefficients of the radome wall and subsequent calculation of the amplitude, phase, polarization and direction of propagation of the reflected plane wave. The extended algorithm demonstrated the ability to predict reflection lobes (also called flash lobes) due to internal radome reflection. Results of this work was presented at the 17th Electromagnetic Window Symposium in July 1984.

C. Spherical Surface Near Field Measurements Technique Development

Significant results were obtained on the modeling of spherical surface near field measurement technique. First, the near field coupling between two antennas, one (a near field probe) moving over a spherical surface centered on the other, (the antenna-under test) was analyzed in terms of the plane wave spectrum of the two antennas versus the previously published spherical mode description of the two antennas. The resulting analysis showed that the polarization of the near field probe was the major compensation factor and that within certain bounds on the electrical size of the near field probe and the seperation distance between the near field probe and the antenna-under-test, the plane was spectrum of the near-field probe could be ignored. A paper describing the research was submitted for publication in the IEEE Transactions on Antennas and Propagation. Second, an investigation was conducted into the magnitude of the Fourier spectral components of the spherical wave functions in order to arrive at a sampling theorem for spherical near field measurements. It was found that due to the slow band-limiting process (at levels of 60 dB below the peak-spectial value) of the spherical modes, that accurate field expansion in spherical modes required an oversampling by a factor of approximately 4/3 with respect to the previously reported Nyguist rate. This results was presented at the U.R.S.I. National Radio Science Meeting in June 1984. Third, a simple algorithm was developed for the compensation of probe position error in spherical near field measurement systems. Position error in theta and phi are compensated using the non uniform Fourier sampling technique and position error in radius is compensated by assuming the dominate spherical mode radial dependence for each measurement point. Thus if the true position of measurement is known, through the use of an high accuracy position measurement system, probe position errors may be removed through software compensation. Simulated results were also presented at the URSI meeting.

PUBLICATIONS:

Short Course Texts:

1. J. Frank and E.B. Joy, Phased Array Antenna Technology, Technology Service Corporation, 1984.

2. E.B. Joy, A.L. Maffett and J. Frank, Radar Cross-Section Measurement Techniques, Technology Service Corporation, 1984.

Editor of Meeting Proceedings:

1. E.B. Joy (Editor), "Near-Field Antenna Measurement Techniques," 1984 Proceedings of the AMTA/IEEE APS Near Field Antenna Measurement Techniques Workshop, p. 85, Boston, MA, June 29, 1984.

Papers in Conference Proceedings:

1. E.B. Joy and J.B. Rowland, Jr., "Spherical Surface Sampling," Proceedings of the U.R.S.I. National Radio Science Meeting," Boston, MA, June 25-28, 1984.

2. E.B. Joy, "Near-Field Measurement Facilities and Research Uses at Georgia Institute of Technology," Proceedings of the AMTA/IEEE APS Near-Field Antenna Measurement Techniques Workshop, pp. 66-70, Boston, MA, June 29, 1984.

3. E.B. Joy and D.E. Ball, "A Fast Ray Tracing Algorithm for Arbitrary Monotonically - Concave Three-Dimensional Radome Shapes," Proceedings of the Seventeenth Symposium on Electromagnetic Windows, p. 59, Atlanta, GA, July 25-27, 1984.

4. E.B. Joy and H.L. Rappaport, "PWS Radome Analysis Including Reflections," Proceedings of the Seventeenth Symposium on Electromagnetic Windows, p. 57, Atlanta, GA, July 25-27, 1984.

5. M.B. Punnett and E.B. Joy, "A Computer Analysis of the RF Performance of a Ground-Mounted Air-Supported Radome," Proceedings of the Seventeenth Symposium on Electromagnetic Windows, pp. 9-16, Atlanta, GA, July 25-27, 1984.

6. E.B. Joy, "A Near-Field Radar Cross-Section Measurement Technique," Proceedings of the Annual Conference of the Antenna Measurement Techniques Association, p. 2B6-1, San Diego, CA, October 2-4, 1984.

7. L.E. Corey and E.B. Joy, "Hexagonal Sampling in Near Field Measurements," Proceedings of the Annual Conference of the Antenna Measurement Techniques Association, pp. 3A4-1-3A4-16, San Diego, CA, October 2-4, 1984.

8. J.A. Donovan and E.B. Joy, "A Cylindrical Near Field Test Facility for UHF Television Transmitting Antennas," Proceedings of the Annual Conference of the Antenna Measurement Techniques Association, p. 4A3-1, San Diego, CA, October 2-4, 1984.

Papers Submitted:

1. W.M. Leach, Jr., "A Plane-Wave Spectrum Development of the Spherical Surface Near-Field Coupling Equation," submitted to the IEEE Transactions on Antennas and Propagation.

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